Coherent Control of Rydberg atoms for Hybrid Quantum Information

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Introduction

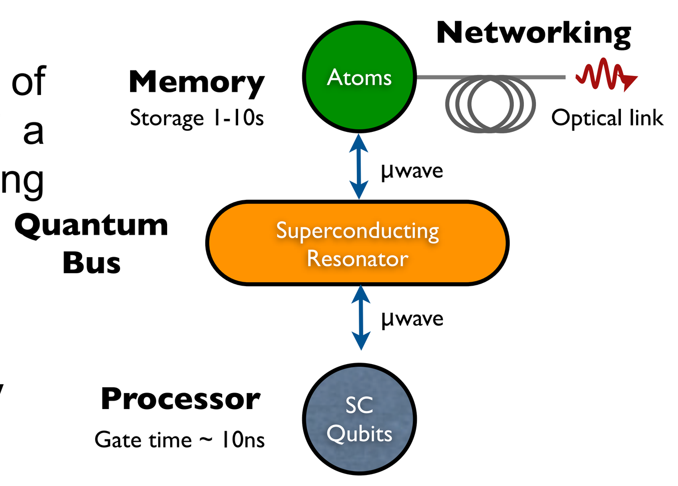
Neutral atoms provide an excellent resource for quantum information processing, combining the long atomic coherence times of the hyperfine ground-states with the strong dipole-dipole interactions of highly excited Rydberg states for generating deterministic entanglement between qubits separated by < 10 μm [1]. Scalable long-range interactions can be obtained by coupling the atomic array to a superconducting microwave cavity enabling hybrid quantum information processing where the cavity-mediated entanglement allows atoms to be coupled over cm length scales.

We present the first steps towards such an experiment incorporating high fidelity readout using an sCMOS camera [2] and the ability to drive fast, optically addressable rotations of the hyperfine-encoded qubits to the Rydberg state. Using our sub-kHz cavity-stabilised laser system [3] we demonstrate coherent control of single Rydberg atoms, performing Ramsey spectroscopy to determine coherence time and to generate entanglement between a pair of atoms separated by 6 μm. Combining this excitation scheme with our ground-state Raman lasers we show progress towards the implementation of a mesoscopic Rydberg gate based on electromagnetically induced transparency (EIT) offering robust entanglement of multi-atom ensembles [4].

Hybrid Quantum Information Processing

Hybrid Quantum Systems

Hybrid quantum computation exploits the unique strengths of disparate quantum technologies, enabling realisation of a scalable quantum device capable of both fast gates and long coherence times.

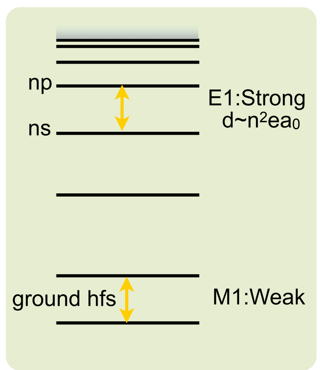


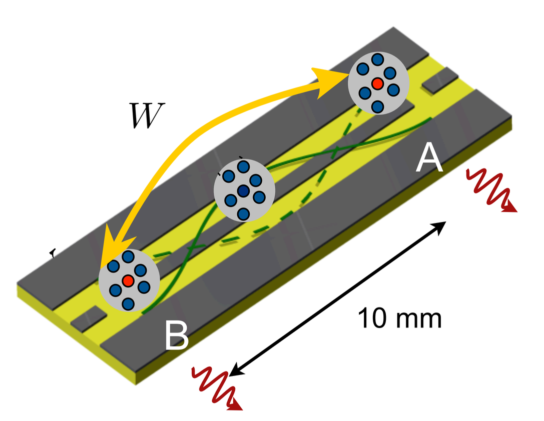
Superconducting qubits coupled via microwave resonators are promising candidates for hybrid systems with both fast gates (GHz) and a scalable architecture but have relatively short coherence times [5].

Atomic qubits have long lifetimes and efficient coupling to optical photons, long coherence times, but slow (MHz) entangling gates via strong Rydberg dipole-dipole interactions [1].

Hybrid Quantum Networking

Quantum networks require hardware to generate entangled photons incorporating quantum memory and integrated processing analogous to "**quantum router**".





Exploit Rydberg electric dipole moment to strongly couple atoms to superconducting microwave circuit [6]. Cavity mediated entanglement provides a scalable long-range interaction [6,7].

L ~ 10 mm >> R_b ~ 5 μm

Entanglement protocol is robust to thermal excitations enabling operation at 4 K [7].

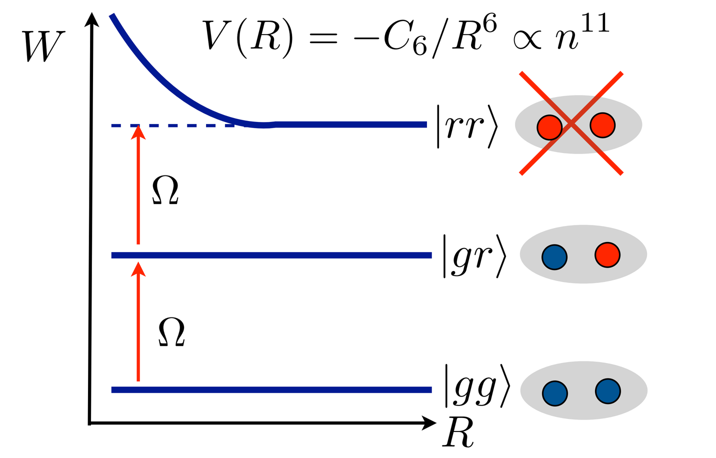
Key Applications

- Enhanced security via quantum cryptography
- Distributed quantum computing
- Optical to microwave conversion (Quantum radar [8])

Ensemble Qubit Gates

Dipole Blockade

Strong dipole-dipole interactions prevent excitation of more than a single Rydberg state for $R < R_b \sim 10\ \mu\mathrm{m}$ [1].

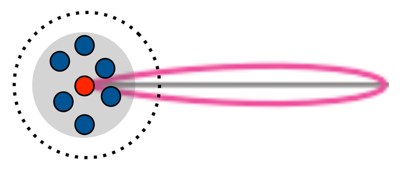


Ensemble Qubits

Exploit blockade to create ensemble qubits - qubit encoded in a shared collective excitation.

$$|\psi\rangle = \frac{1}{\sqrt{N}}\sum_i e^{-i\boldsymbol{k}\cdot\boldsymbol{r}}|r\rangle_i$$

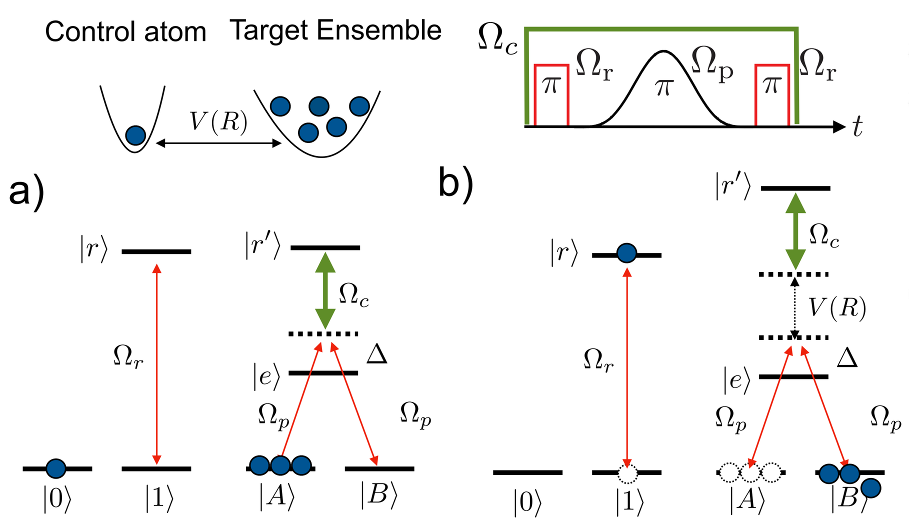
- ➡ Strong atom-photon coupling without cavity
- ➡ Cooperative, directional photon emission
- ➡ Efficient coupling to single mode fiber
- ➡ Ensemble qubits robust to atom loss



$\sqrt{N}$ Enhancement

Mesoscopic gate protocol

Collective enhancement leads to number dependent pulse durations leading to low fidelity for atomic shot noise. Müller *et al.* provide alternative EIT gate protocol for ensemble qubits [4].



a) For control atom in state $|0\rangle$ the ensemble adiabatically follows dark state

$$|0\rangle_c|A\rangle_t \rightarrow |0\rangle_c|A\rangle_t$$

b) For control atom in $|1\rangle$ blockade detunes EIT condition enabling Raman transfer

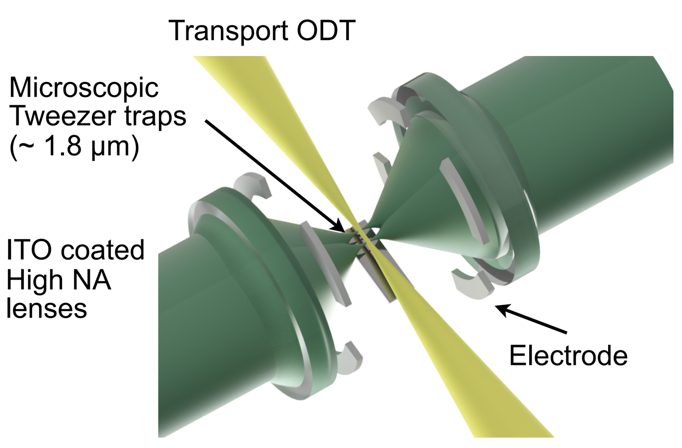
$$|1\rangle_c|A\rangle_t \rightarrow |1\rangle_c|B\rangle_t$$

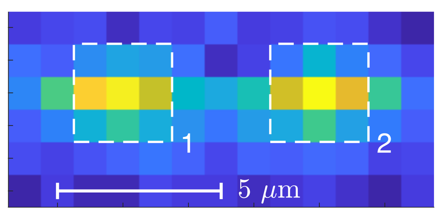
Implements high fidelity C-NOT^N gate

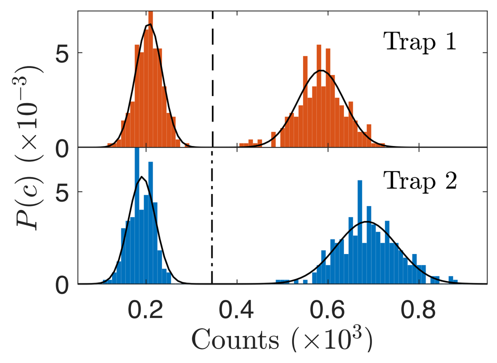
Experiment Setup

Single Atom Trapping

Cs atoms cooled in MOT before being optically transported 30 cm to UHV science cell where they trapped in microscopic tweezer traps separated by 6 μm.





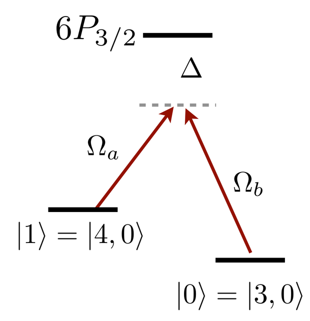


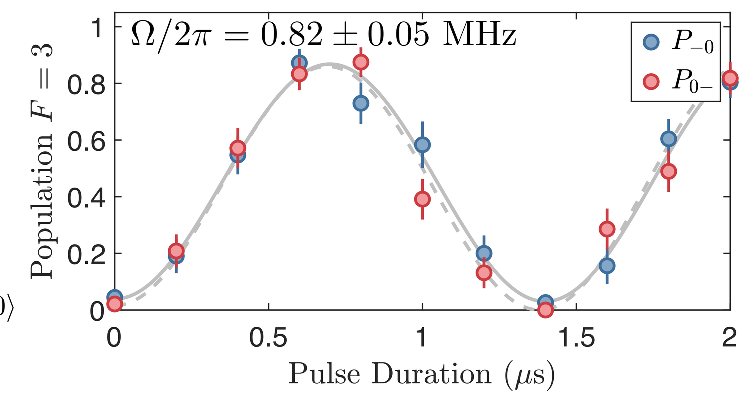
Atoms detected using sCMOS camera to achieve high fidelity readout (error $\varepsilon < 10^{-6}$) with 1 μm spatial resolution [2].

Achieve ~90% clock-state preparation at a temperature of ~10 μK following adiabatic ramping of trap depth to 300 μK.

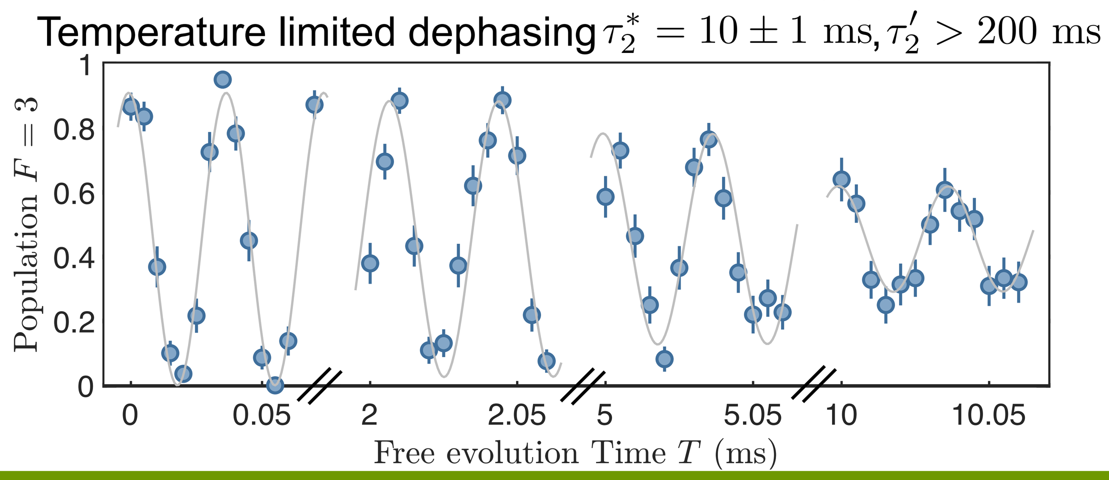
Ground-state rotations

Single qubit operations performed using two-photon transitions detuned $\Delta/2\pi = -45$ GHz from resonance.

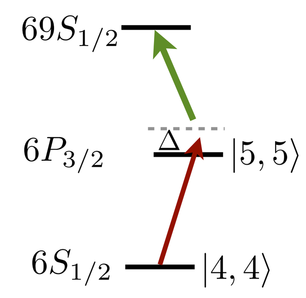




Temperature limited dephasing $\tau_2^* = 10 \pm 1$ ms, $\tau_2' > 200$ ms



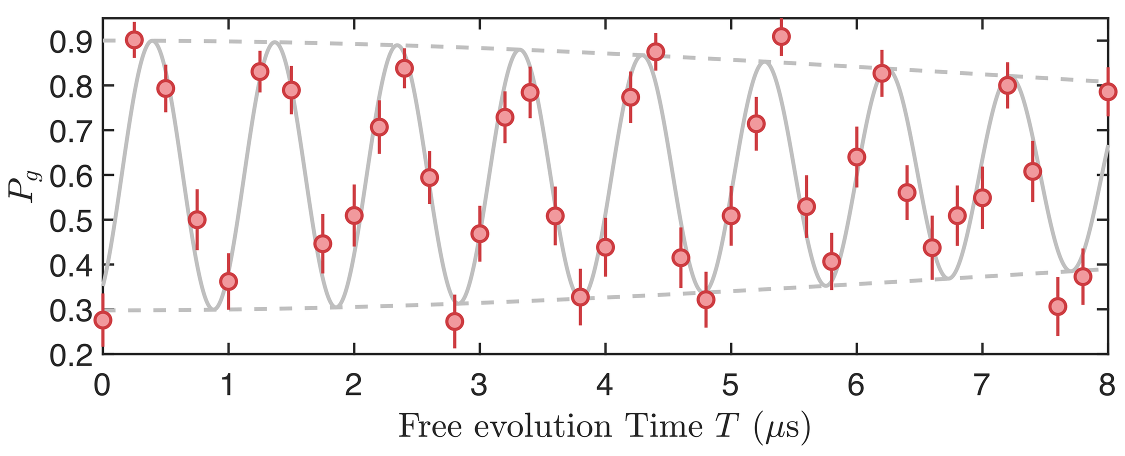
Rydberg Excitation



Two-photon excitation to Rydberg via D_2 line. Lasers stabilised to high-finesse ULE cavity with relative linewidth < 200 Hz and <1 Hz/s drift rate [3].

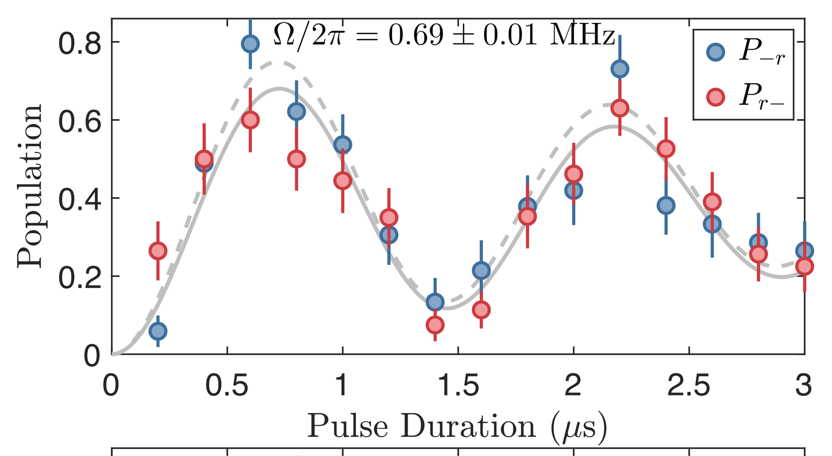
Beams focused to 4.6 μm (852 nm) and 18 μm (509 nm) in counter-propagating geometry, powers 570 nW and 90 mW respectively, $\Delta/2\pi = +891$ MHz.

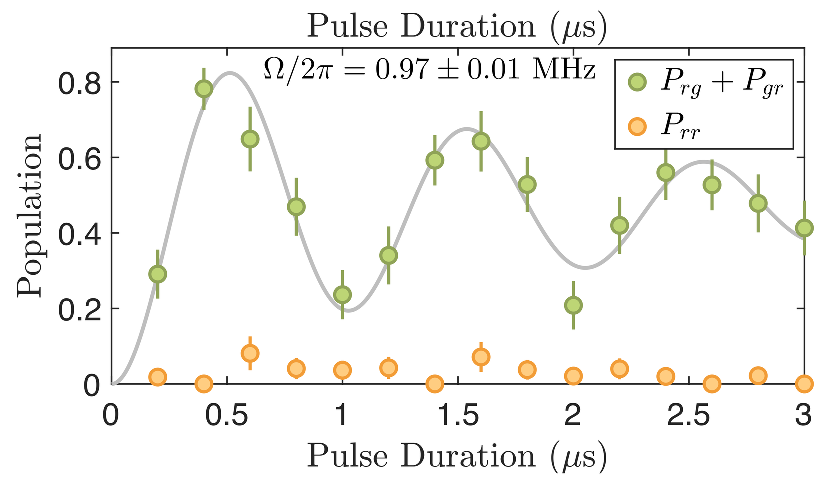
Achieve ~MHz two-photon Rabi frequency - measure single atom coherence time via Ramsey fringes - obtain $\tau_2^* = 15 \pm 3\ \mu s$.



Two-Atom Entanglement

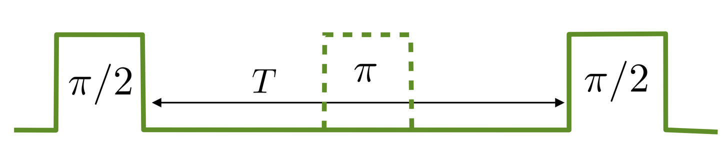
Entanglement observed for two atoms at 6 μm separation - see $\sqrt{2}$-enhancement in excitation to singly excited state and suppression of $P_{rr} < 5\%$.

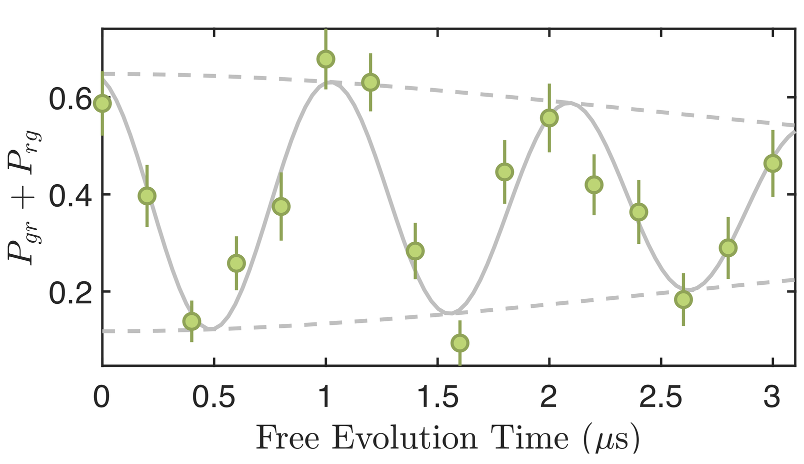




Atoms excited to $|\psi\rangle = (|rg\rangle + |gr\rangle)/\sqrt{2}$

$$R_b = \sqrt[6]{|C_6|/\Omega} \sim 9.5\ \mu m$$

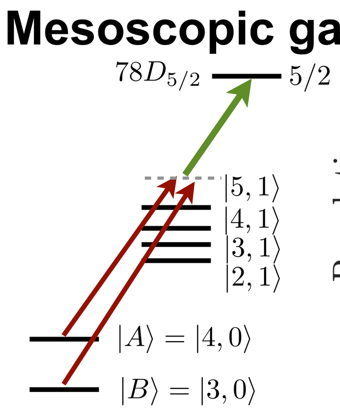


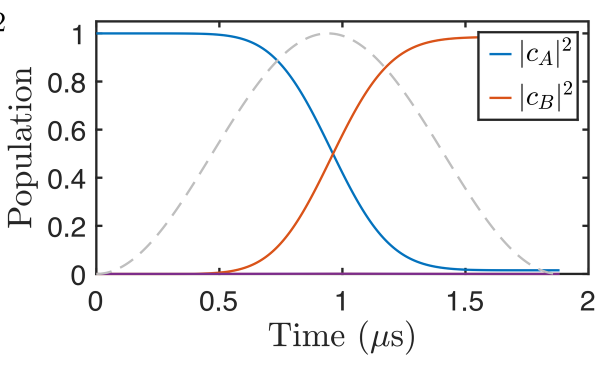


Obtain $\tau_2^* = 4.7 \pm 0.5\ \mu s$ and $\tau_2' > 40\ \mu s$ using echo. Coherence > required gate time.

Outlook

Mesoscopic gate in multilevel atom



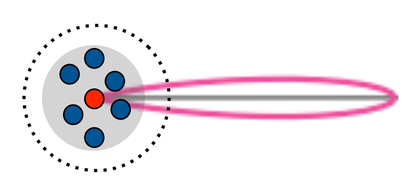


$|0\rangle_c|A\rangle_t \rightarrow |0\rangle_c|A\rangle_t$
$\mathcal{F} = 0.999$

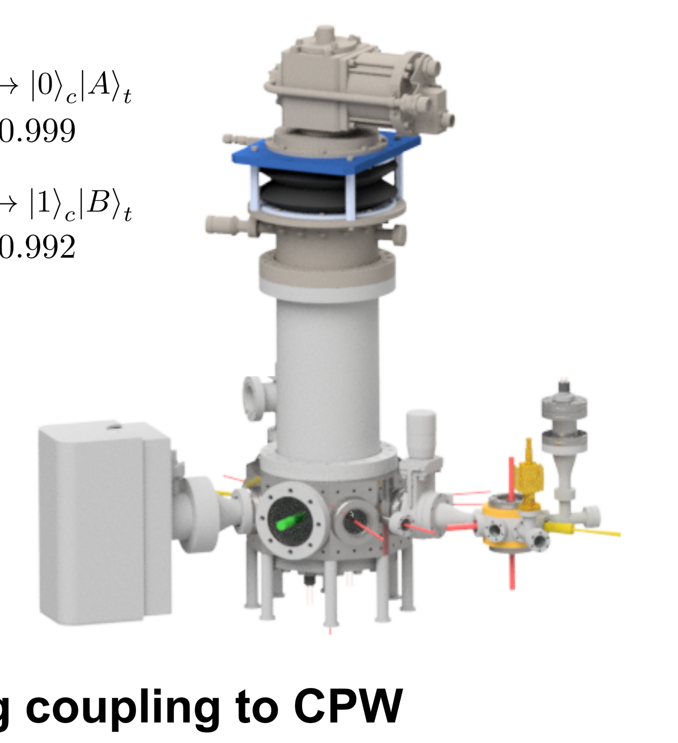
$|1\rangle_c|A\rangle_t \rightarrow |1\rangle_c|B\rangle_t$
$\mathcal{F} = 0.992$

Analysis of gate protocol for multilevel atom shows $nD_{5/2}$ m_j=5/2 gives optimal performance. Graph shows simulation for $78D_{5/2}$ with current beam waists and powers yielding F>0.99.

Ensemble qubits



Increase trap size to enable loading of atomic ensembles - explore application of atomic ensembles as directional photon sources.



Strong coupling to CPW

Upgrade experiment setup to install 4 K closed-cycle UHV cryostat and trap atoms close to high Q superconducting resonator

References

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